EFFECTS OF MULTIPLE EXITS
SMALL-SCALE MODEL TEST RESULTS

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Small-scale high explosive tests were performed to determine if two exits instead of a simple exit from an underground magazine chamber would reduce the external blast hazard from an accidental explosion. The results indicate that Inhabited Building Distance for airblast from one exit is not significantly reduced by the existence of another exit from the underground magazine.

INTRODUCTION AND BACKGROUND

The U.S. Army Engineer Waterways Experiment Station (WES) is conducting research, under the Joint U.S./Korea R&D Study for New Underground Ammunition Storage Technologies, on airblast effects from explosions in underground ammunition storage facilities. The purpose of the research is to develop magazine design enhancements which would minimize the airblast Inhabited Building Distance (IBD) should an accidental internal detonation occur. Current U.S. DOD Explosives Safety Standards require the addition of predicted overpressures from all openings from an explosion in an underground magazine to establish the airblast IBD. Contributions from all openings with cross-sectional area greater than five percent of the largest opening must be considered. Exceptions to the U.S. regulations are allowed if they can be justified based on experimental data or analysis.

NATO criteria allows a factor of two reduction in the explosive quantity used in the airblast IBD computations when the underground facility has multiple openings, and where the blast waves from these exits are not expected to interact to cause a significant increase in far-field overpressures. In effect, this allows a reduction of the IBD by a factor equal to the cube root of two, for underground storage facilities with multiple openings which satisfy these criteria.

The results of model tests to investigate the effects of multiple (two) exits are presented in this paper. Conclusions are drawn regarding the effect of two exits with sufficient separation so that there is no significant blast wave interaction.

DESCRIPTION OF EXPERIMENT

Seven small-scale explosive experiments were performed. Four tests were conducted with two open exits (Figure 1). One of these exits was closed for the remaining three tests (Figure 2). The internal test geometry was identical for all tests to eliminate the effects of internal volumes as a variable. The

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test series consisted of four experiments at simulated (TNT-equivalent) chamber loading densities of I, 5, 15, and 42 kg/m^3 not repeated due to overstressing of the closure plate by the 15 kg/m^3 test)

The test assembly included a 1.8-m long by 146-mm diameter steel detonation chamber. The detonation chamber was egressed at both ends by smooth-wall, steel pipe sections 4-m long by 73.7-mm in diameter. High strength steel bolts were used for the connections between the exit pipe and the chamber, and for the end plate (one exit open).

Composition 4 (C-4) explosives were used for all seven experiments. The explosive charges were square in cross-section (50.8 mm) with their lengths varied to produce the required charge weights. The charges were centered inside the detonation chamber, and were center-detonated, using exploding bridge wire (EBW) detonators.

The charge weights used for the four chamber loading densities were 23, 113, 340, and 952 g, which (assuming a 1.34-to-1.00 C-4 to TNT explosive equivalency) provided the TNT-equivalent loading densities of 1, 5, 15, and 42 kg/m^3.

Instrumentation to measure the induced airblast pressures consisted of 12 airblast gages located along the interior surface of the vent pipe, and 10 external airblast pressure gages located on the ground surface along the extended centerline of the exit pipe. Kulite Corporation Model HDS-375 pressure transducers were used for the internal airblast measurements. The internal gages were flush-mounted to the inner walls of the pipe sections (side-on pressure measurements). These pressure transducers had dynamic ranges of 210 MPa to 3.4 MPa, with associated resonant frequencies of 735 to 650 kHz.

The external measurements employed Kulite Model XT-190 airblast gages. These instruments had dynamic ranges between 13.8 MPa and 35 kPa, and associated resonant frequencies between 650 kHz and 70 kHz. The free-field gages were mounted flush to the ground surface beyond the ends of the exit pipes at ranges (from the exit) of 3.05, 6.1, 12.2, and 24.4 m.

BLASTX3 CALCULATIONS

A computational model of the small-scale experiment was developed using BLASTX3, a WES-developed, empirical-based airblast code. This code has undergone a recent revision to allow calculation of airblast propagation in tunnels for moderate to large chamber loading densities (charge weight per cubic meter of chamber volume). Data from the WES small-scale model test program and one-dimensional hydrocode calculations were used in developing the improved version of the code (BLASTX3).

Two experiments, both with explosive loading densities of 15 kg/m^3, with one and two exits, were calculated with the BLASTX3 computational model. The physical model was divided into cylindrical sections with an approximate length to diameter aspect ratio of 3:1 for the computational model. The length-to-diameter ratio of the model detonation chamber was 12.3:1. Similarly, the exit tunnels at opposite ends of the detonation chamber were divided into 18 equal cylindrical sections, each with an aspect ratio of 3:1.

Since BLASTX3 can only model spherical charges, the cylindrical charge used in the experiments was represented by two adjacent spherical charges in the computational model. The two charges were detonated simultaneously in the calculation.

RESULTS OF EXPERIMENTS AND CALCULATIONS

Peak internal overpressure data from the experiments conducted with the four different loading densities are presented in Figures 3, 4, 5, and 6, respectively. These figures show only the tunnel pressures, measured between the chamber and the portal. For peak pressure, the plots indicate that any effect of the number of exits is obscured by the inherent scatter of the data. A comparison with the internal gas pressures calculated by BLASTX3 is shown in Figure 5. Although the calculated values are approximately one-half those measured in the tests, both sets of data follow the same trend. As shown in Figure 5, the calculated peak internal pressures for the chamber with one exit overlays the peak data for the chamber with two exits.

Similar plots comparing peak side-on impulse data in the tunnels from these experiments are presented in Figures 7, 8, 9, and 10. Although there is considerable data scatter, the peak values from the experiments with two exits seemed to be only slightly higher than similar data from tests with one exit, for the 1 and 5 kg/m^3 loading densities.

Normalized peak overpressure data recorded in the free-field beyond the tunnel portals are plotted versus reduced distance in Figures 11, 12, 13, and 14. The non-dimensional pressure values were obtained by dividing the calculated effective exit pressure by the peak free-field pressure (DDESB, 1993). The effective exit pressure is calculated from

EQUATION

$$P = 1770.5 \left(\frac{Q}{V^t}\right)^{\frac{1.35}{3}}$$

where, Q is the net explosive weight in the chamber, kg and V_t is the total volume of the underground storage system, m^3.

The reduced distances were computed by dividing the distances from the exit portal by the hydraulic diameter for turbulent flow, which is obtained from

$$D = \frac{4A}{P}$$

where A is the minimum cross-sectional area of the portal, m^2 and p is the perimeter of the minimum cross-section, m.

The normalized free-field pressure indicates no significant influence of chamber loading density (Figures 11, 12, 13, and 14, respectively). The peak data from experiments with one exit compared to the result from two exits do not indicate any significant differences between the two data sets. In Figure 13, the normalized peak pressures in the free-field as calculated by BThASTX3 are also shown (for the 15 kg/m^3 loading density). The normalized BLASTX3 data from the one and two exit computational models show identical peak data for both models.

Peak free-field impulse data are plotted versus reduced distance in Figures 15, 16, 17, and 18. The peak data from tests with one exit fall within the data scatter of peak values from tests with two exits. The BLASTX3 calculated peak free-field impulse values for the 15.0 kg/m^3 loading density are shown in Figure 17. Although the calculated peak values are a factor of 3 or 4 lower than the experimental data, the calculated peak values from the one and two exit models are again identical.

CONCLUSIONS

The results of small-scale experiments and BLASTX3 calculations indicate that two exits from a detonation chamber do not significantly reduce the blast pressure and impulse in the tunnels and the exterior free-field, compared to a chamber with only one exit. The peak overpressure and impulse are primarily a function of the chamber loading density and (intuitively) the exit tunnel diameter.

RECOMMENDATIONS

Additional testing with two exits to quantify the effect of blast field interaction on Inhabited Building Distance.

ACKNOWLEDGEMENTS

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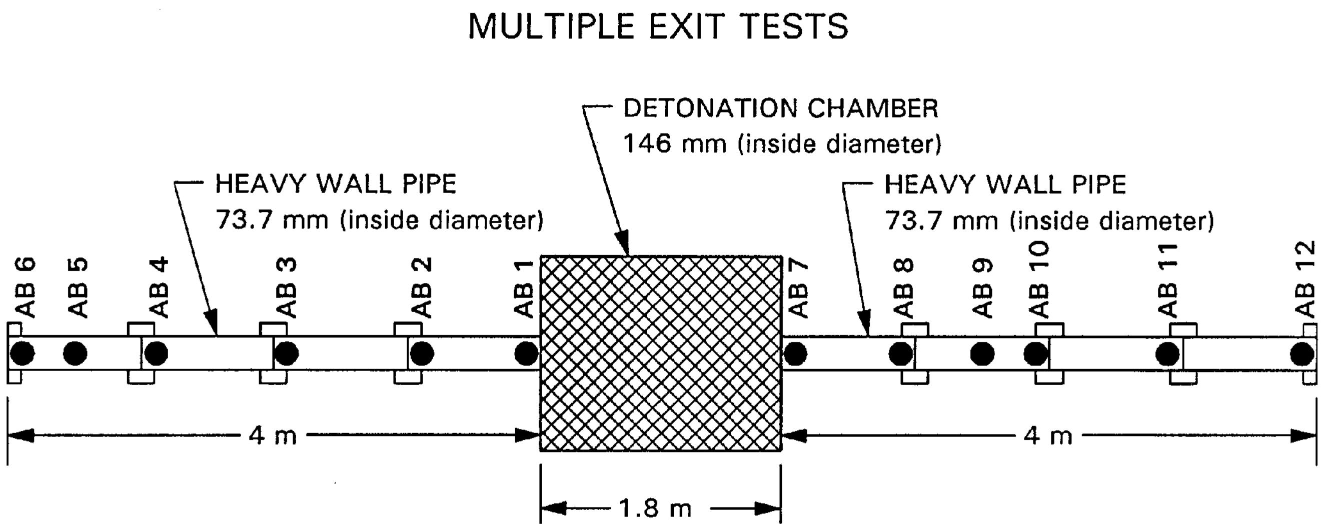
Figure 1.
Multiple exit test series: plan view of test layout for chamberswith two exits



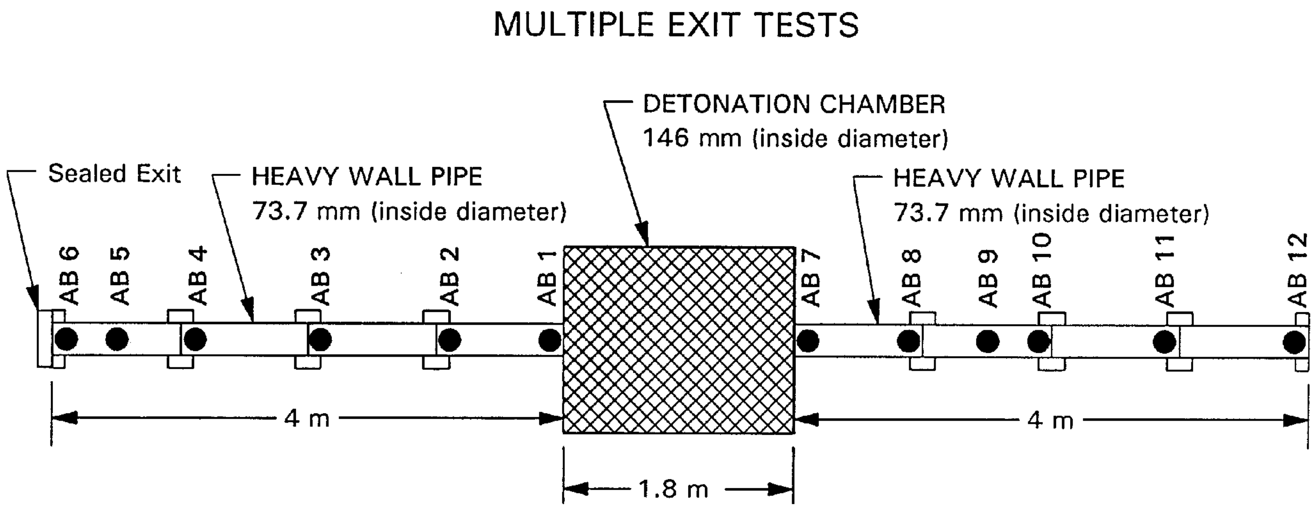
TEST NO.	LOADING DENSITY kg/m^3
111	1.0
112	5.0
113	15.0
114	42.0

FREE-FIELD GAGE LOCATIONS

GAGE NO.		
RIGHT	LEFT	FROM PORTAL m
AB 18	AB 13	3.06
AB 19	AB 14	6.1
AB 20	AB 15	6.1
AB 21	AB 16	12.2
AB 22	AB 17	24.4

Figure 1. Multiple exit test series: plan view of test layout for chamberswith two exits

Figure 2.
Multiple exit test series: plan view of test layout for chamberswith one exits



TEST NO.	LOADING DENSITY kg/m^3
115	1.0
116	5.0
117	15.0

FREE-FIELD GAGE LOCATIONS

GAGE NO.	FROM PORTAL m
AB 13	3.06
AB 14	6.1
AB 15	6.1*
AB 16	12.2
AB 17	24.4

Figure 2. Multiple exit test series: plan view of test layout for chamberswith one exits

Figure 3. Cornparison of peak overpressure in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

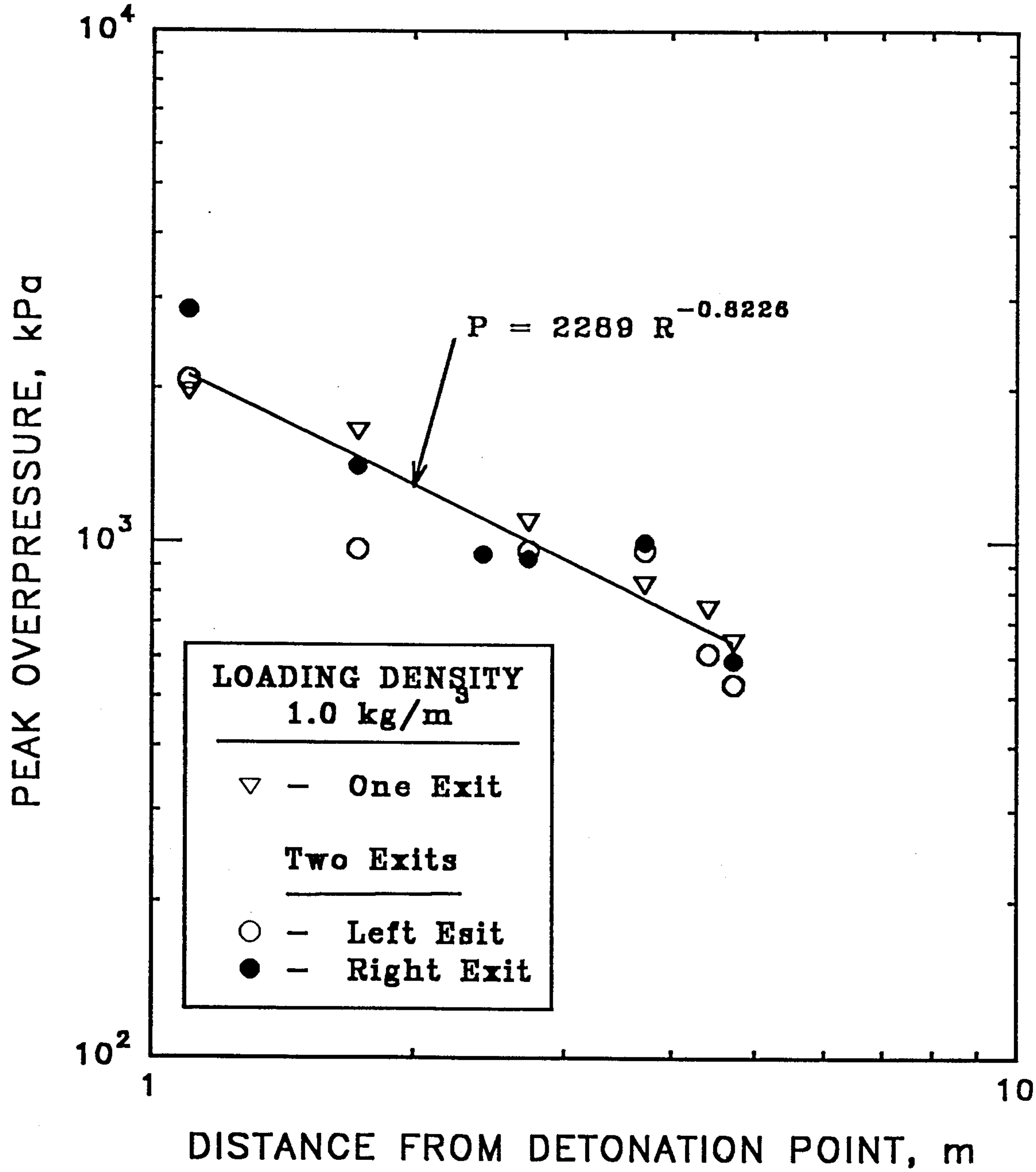


Figure 3. Comparison of peak overpressure in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

Figure 4. Comparison of peak overpressure in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 5.0 kg/m^3.

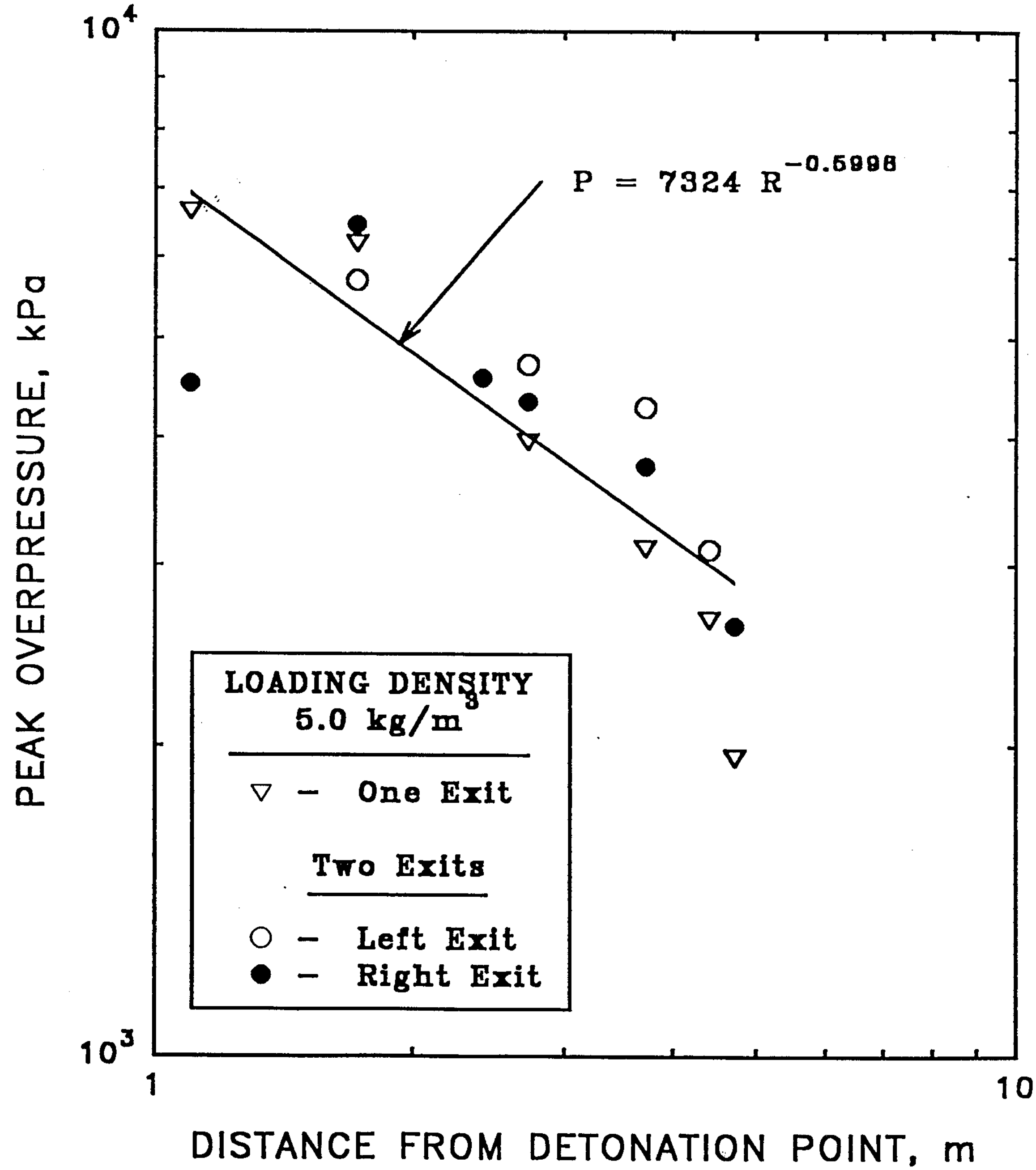


Figure 4. Comparison of peak overpressure in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 5.0 kg/m^3.

Figure 5. Comparison of peak overpressure in tunnels from experimental and computational (BIASTX3) models of detonations in chambers with two exits versus chambers with one exit, for an explosive loading density of 15.0kg/m³.

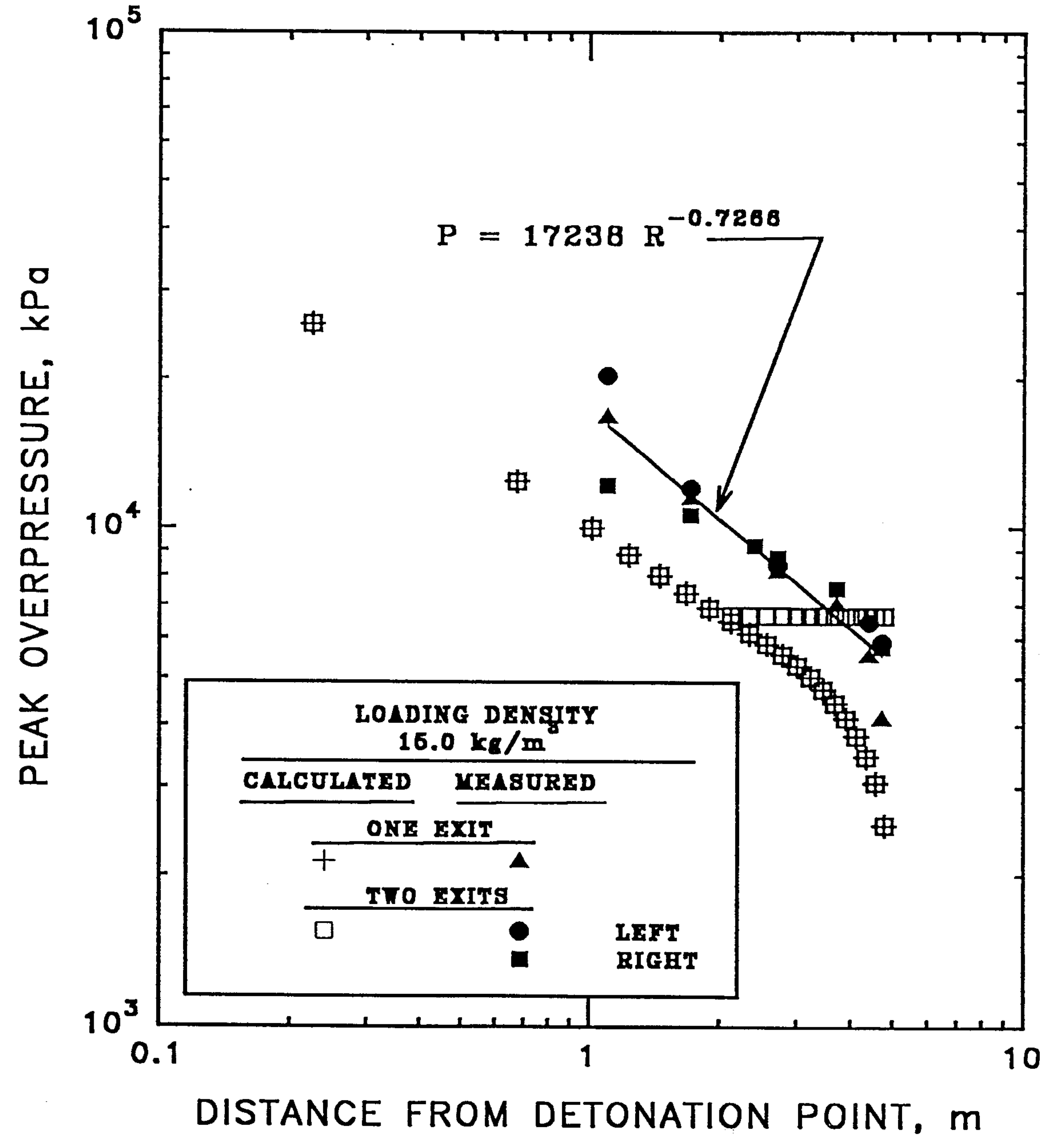


Figure 5. Comparison of peak overpressure in tunnels from experimental and computational (BLASTX3) models of detonations in chambers with two exits versus chambers with one exit, for an explosive loading density of 15.0 kg/m³.

Figure 6. Comparison of beak overpressure in tunnels from detonations with two exits, left side (open circles) versus right side (solid circles), for an explosive loading density of 42.0 kg/m³.

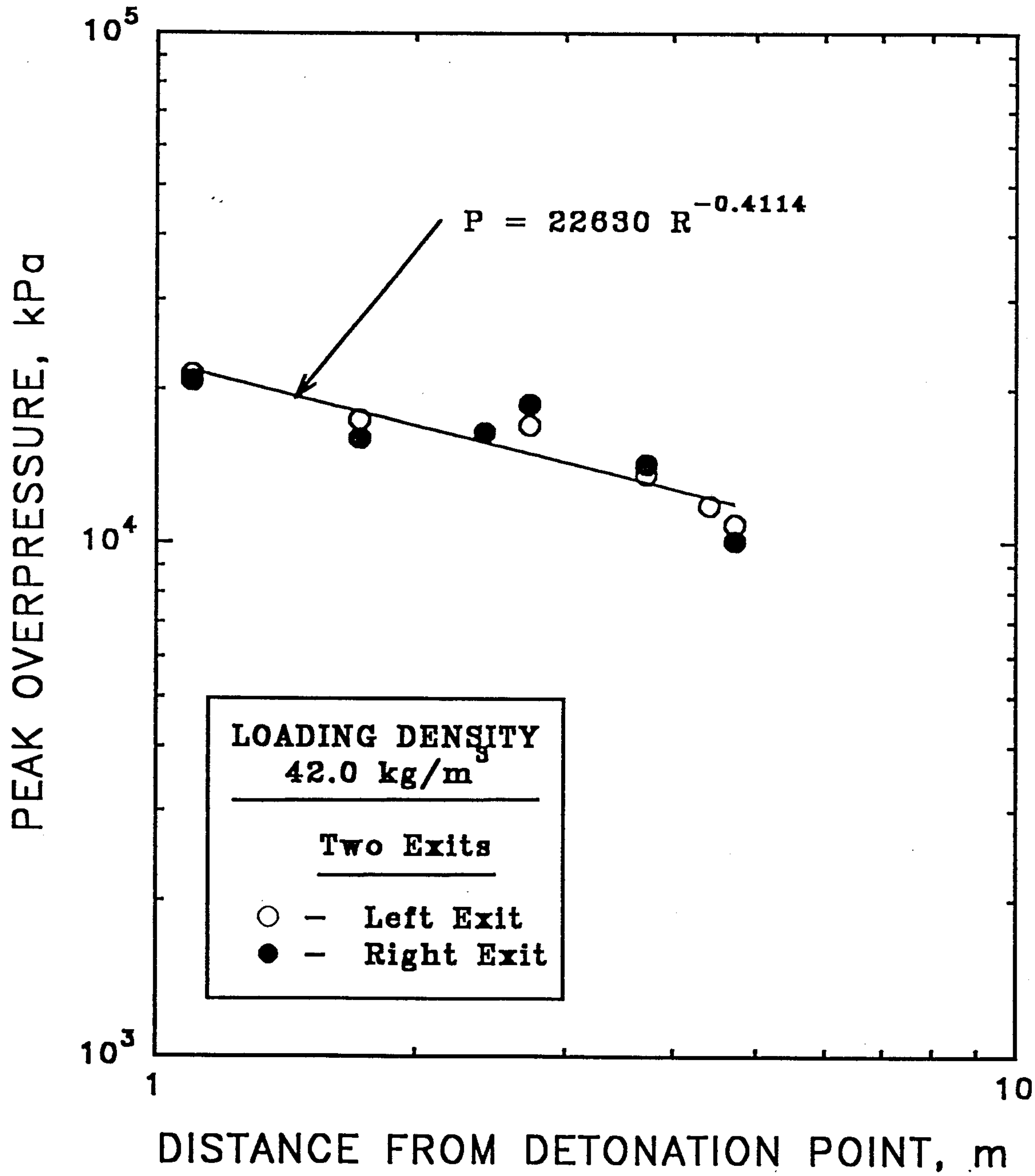


Figure 6. Comparison of peak overpressure in tunnels from detonations with two exits, left side (open circles) versus right side (solid circles), for an explosive loading density of 42.0 kg/m³.

Figure 7. Comparison of peak side-on impulse in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

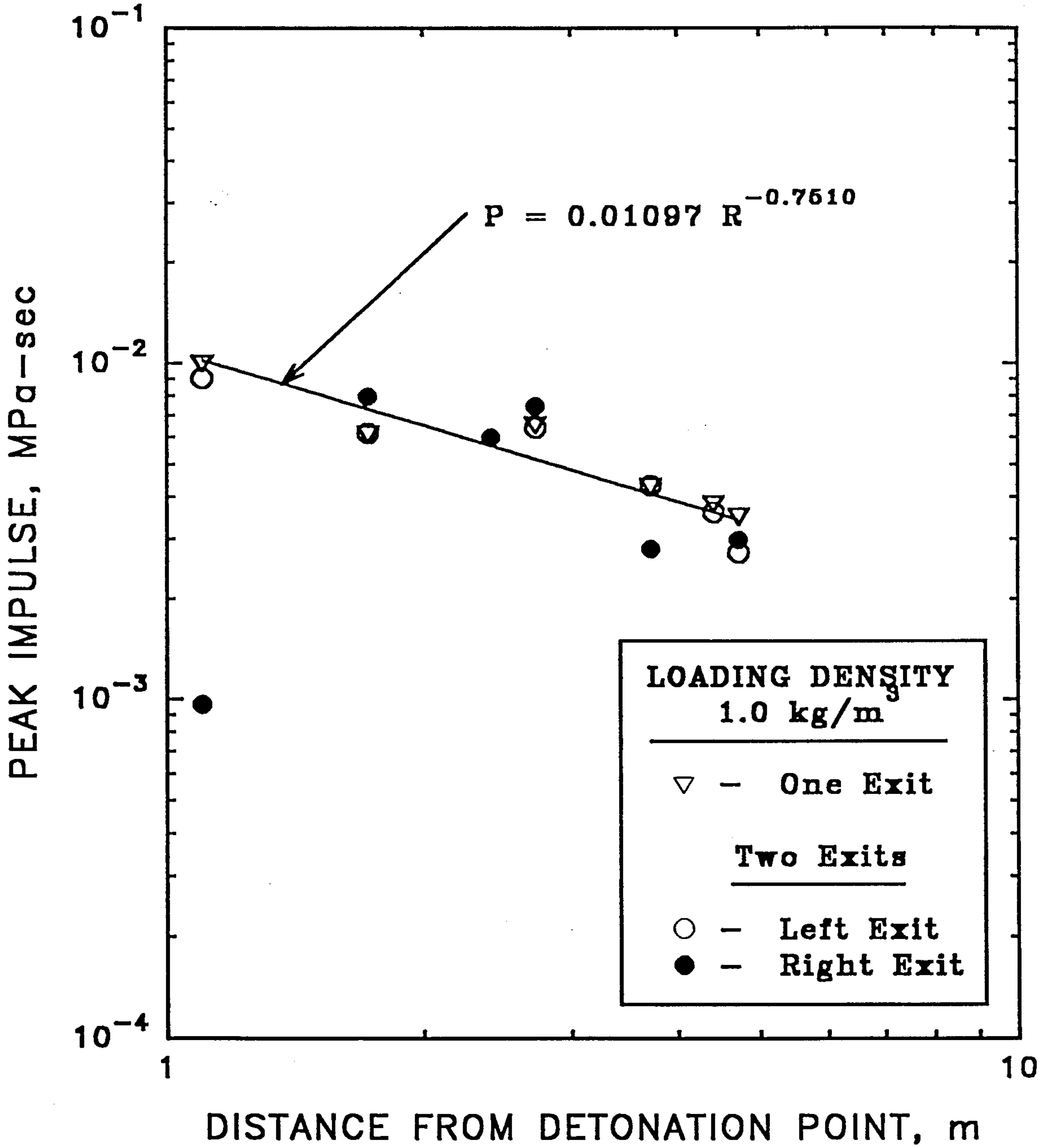


Figure 7. Comparison of peak side-on impulse in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

Figure 8. Comparison of peak side-on impulse in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 5.0 kg/m³.

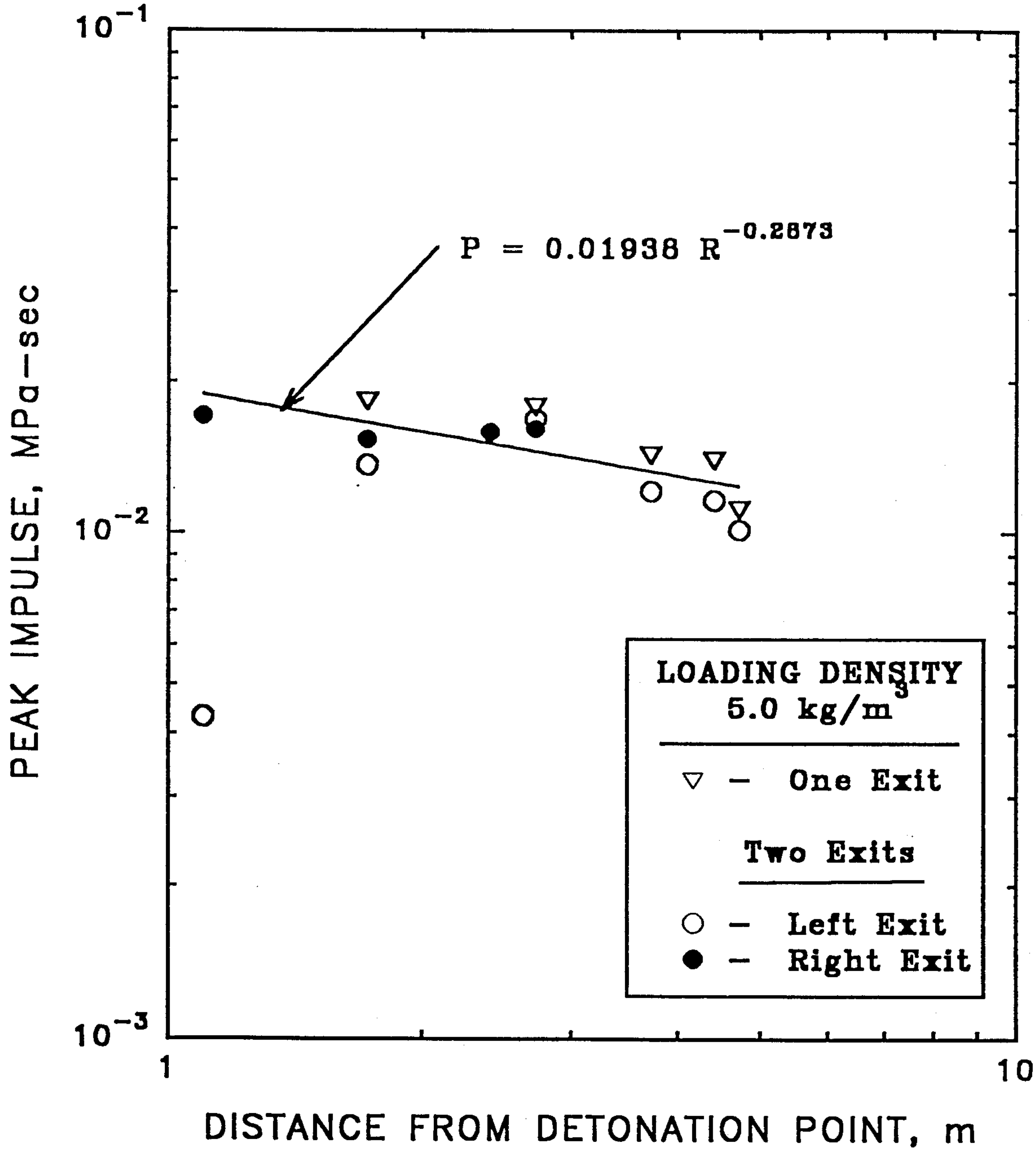


Figure 8. Comparison of peak side-on impulse in tunnels from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 5.0 kg/m³.

Figure 9. Comparison of peak side-on impulse in tunnels from detonations in chambers with two exits (circles)versus chambers with one exit (triangles), for an explosive loading density of 15.0 kg/m³.

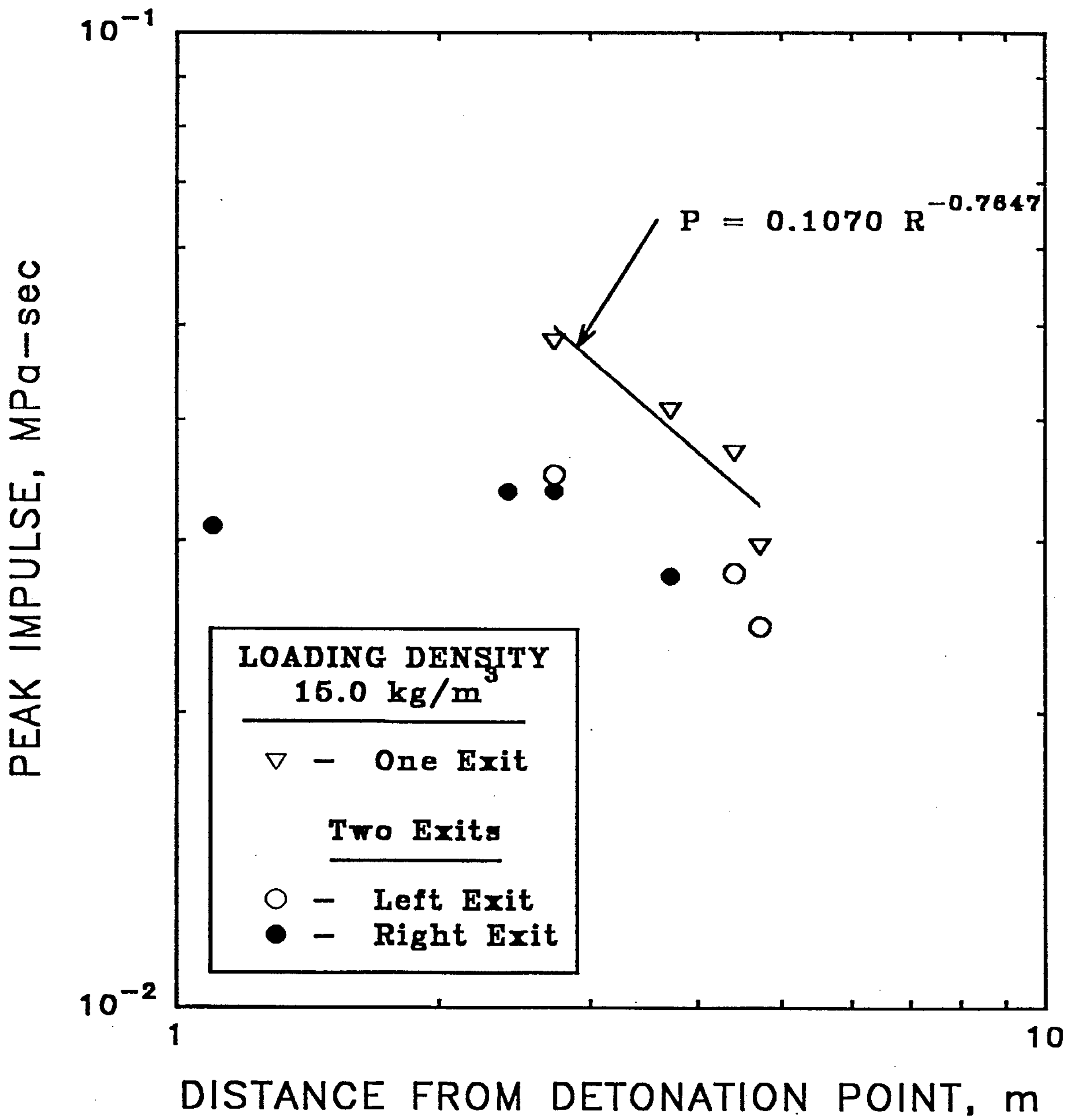


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Figure 10. Comparison of peak side-on impulse in tunnels from detonations with two exits, left side (open circles) versus right side (solid circles), for an explosive loading density of 42.0 kg/m^3.

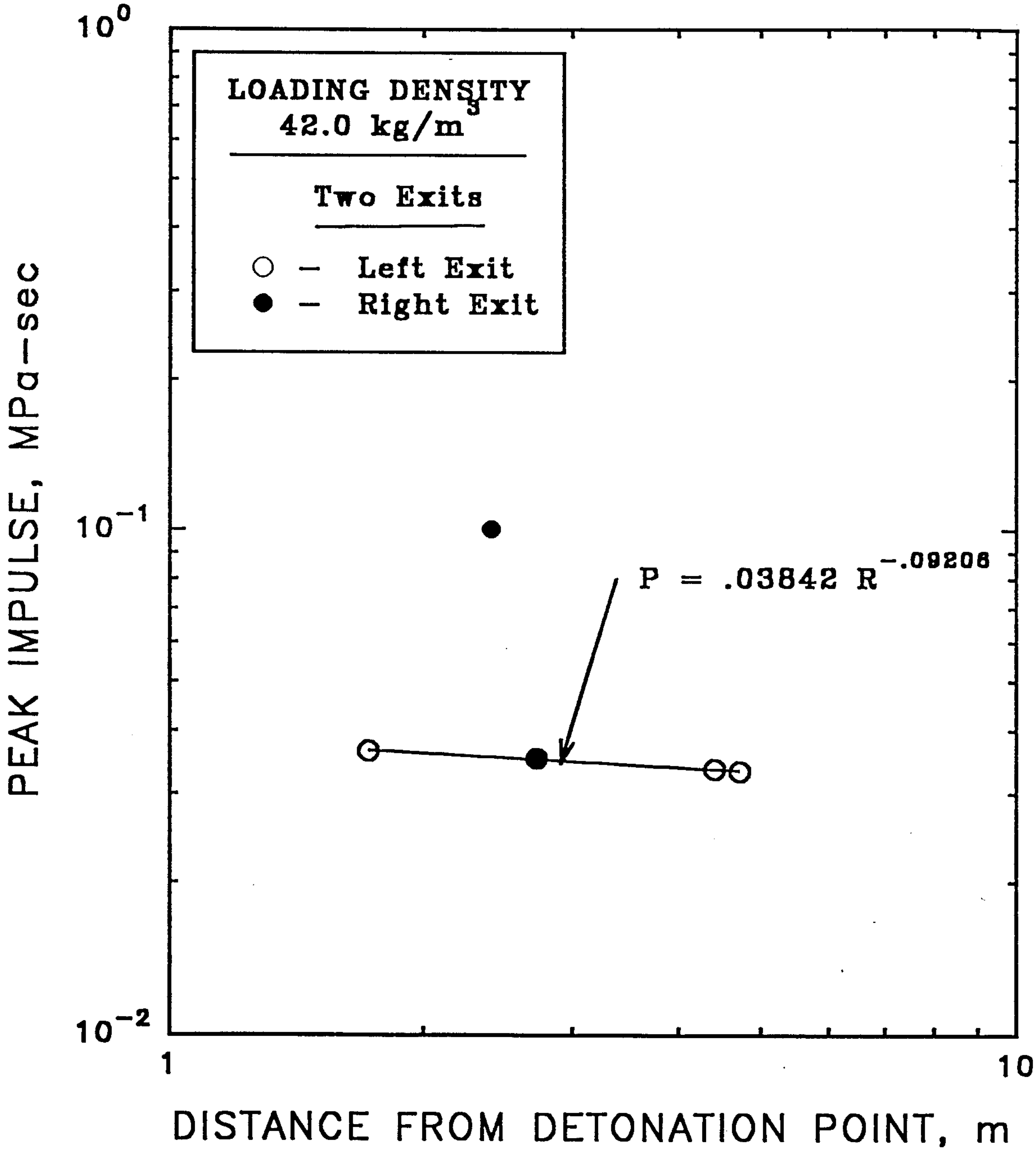


Figure 10. Comparison of peak side-on impulse in tunnels from detonations with two exits, left side (open circles) versus right side (solid circles), for an explosive loading density of 42.0 kg/m^3.

Figure 11.Comparison of normalized free-field overpressures from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

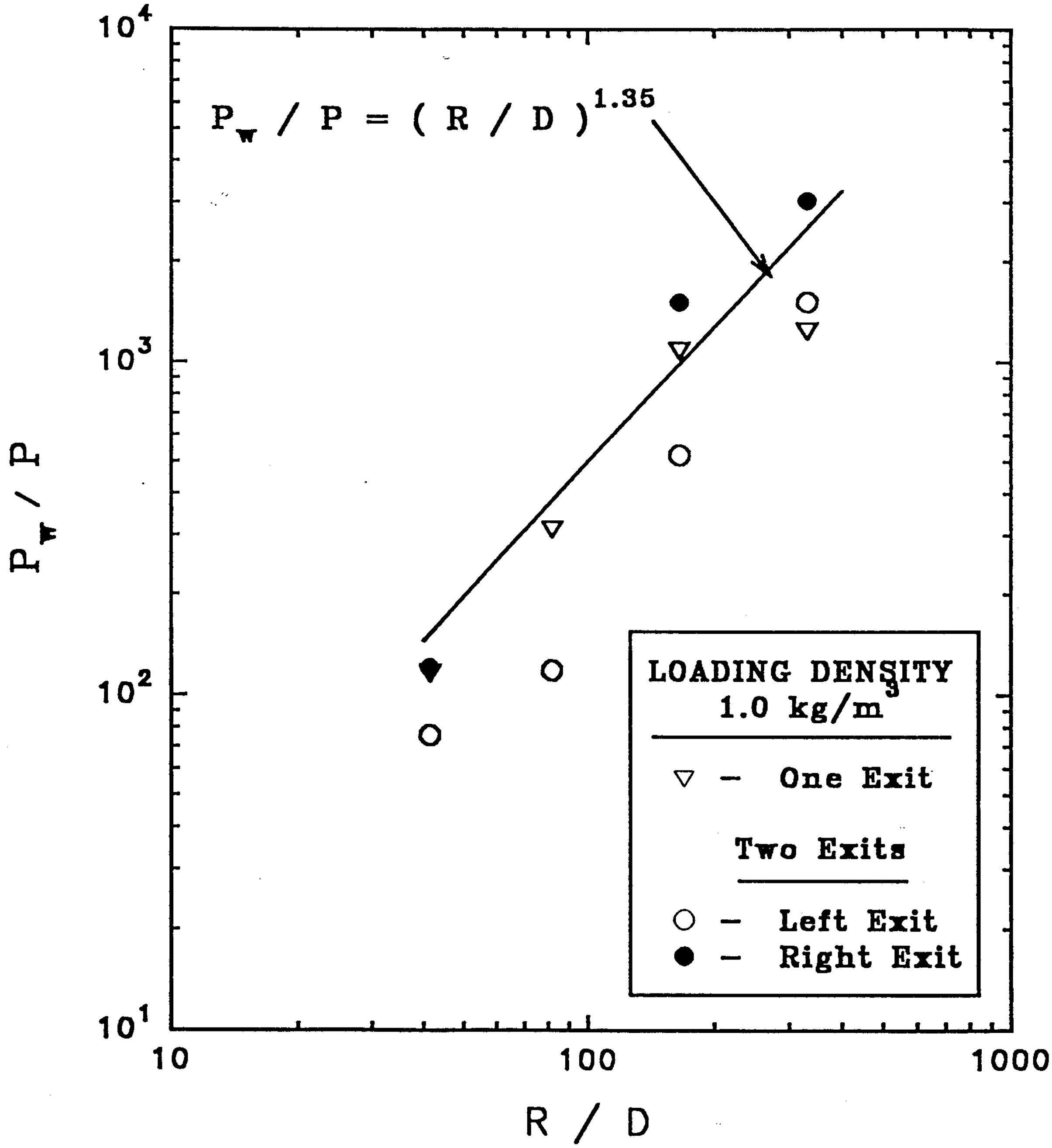


Figure 11. Comparison of normalized free-field overpressures from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

Figure 12. Comparison of~norrnalized free-field overpressures detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 5.O kg/m³.

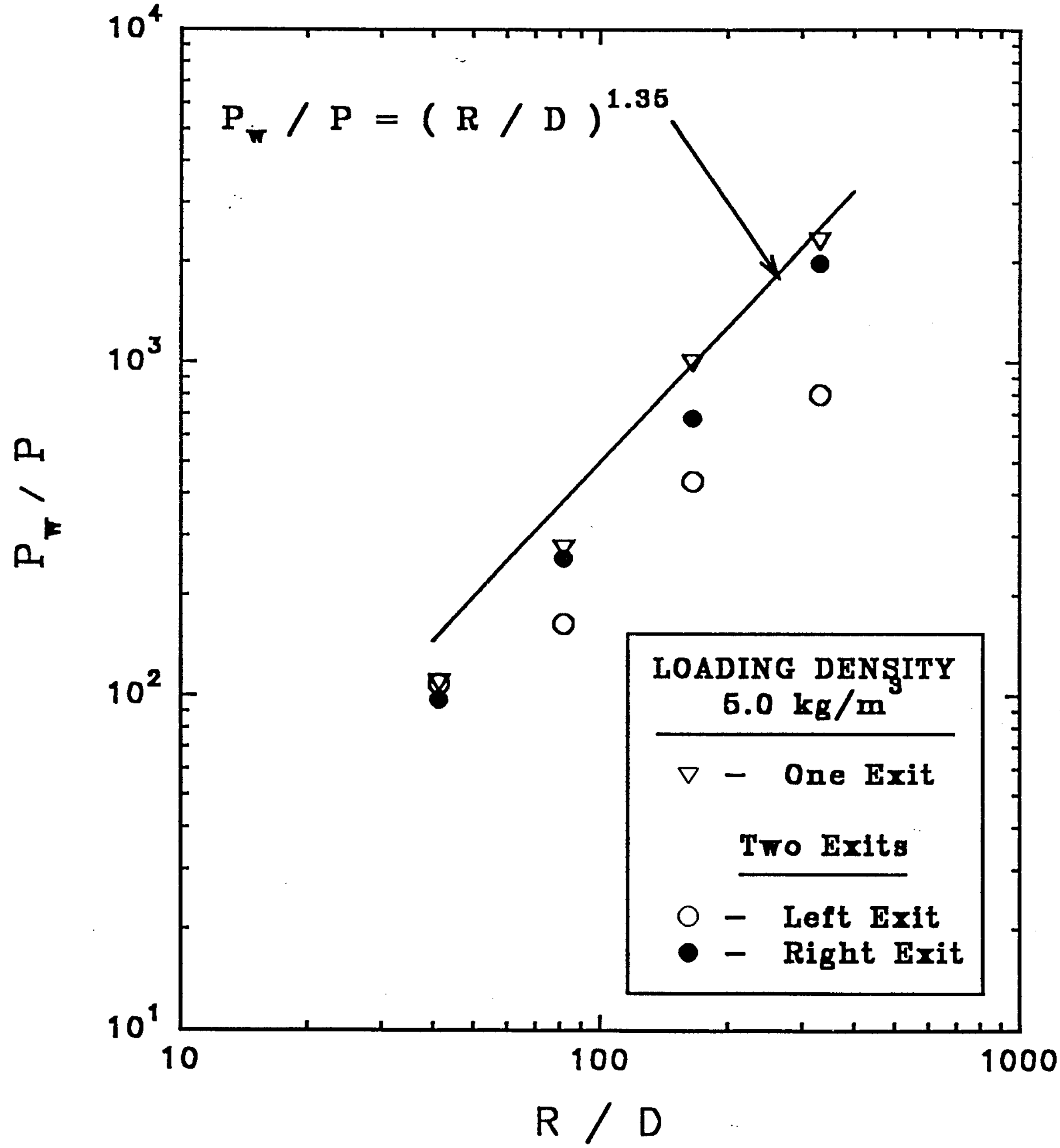


Figure 12. Comparison of normalized free-field overpressures from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 5.0 kg/m³.

Figure 13. Comparison of normalized free-field overpressures from experimental and computational (BIASTX3) models of detonations in chambers with two exits versus chambers with one exit, for an explosive loading density of 15.0 kg/m³.

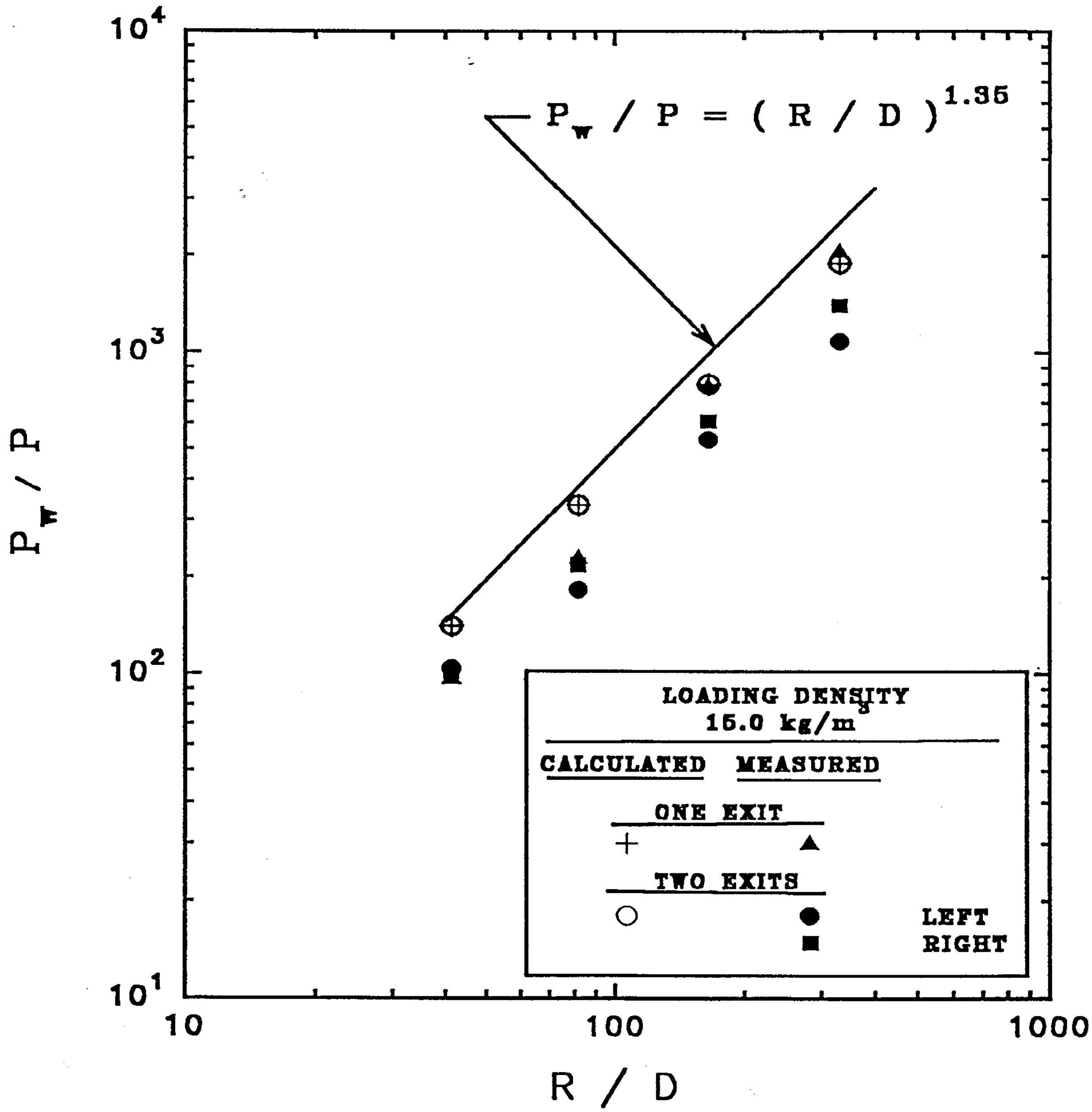


Figure 13. Comparison of normalized free-field overpressures from experimental and computational (BLASTX3) models of detonations in chambers with two exits versus chambers with one exit, for an explosive loading density of 15.0 kg/m³.

Figure 14. Comparison of normalized free-field overpressures from detonations in chambers with two exits, left side (open circles) versus right side (solid circles) for an explosive loading density of 42.0 kg/m^3.

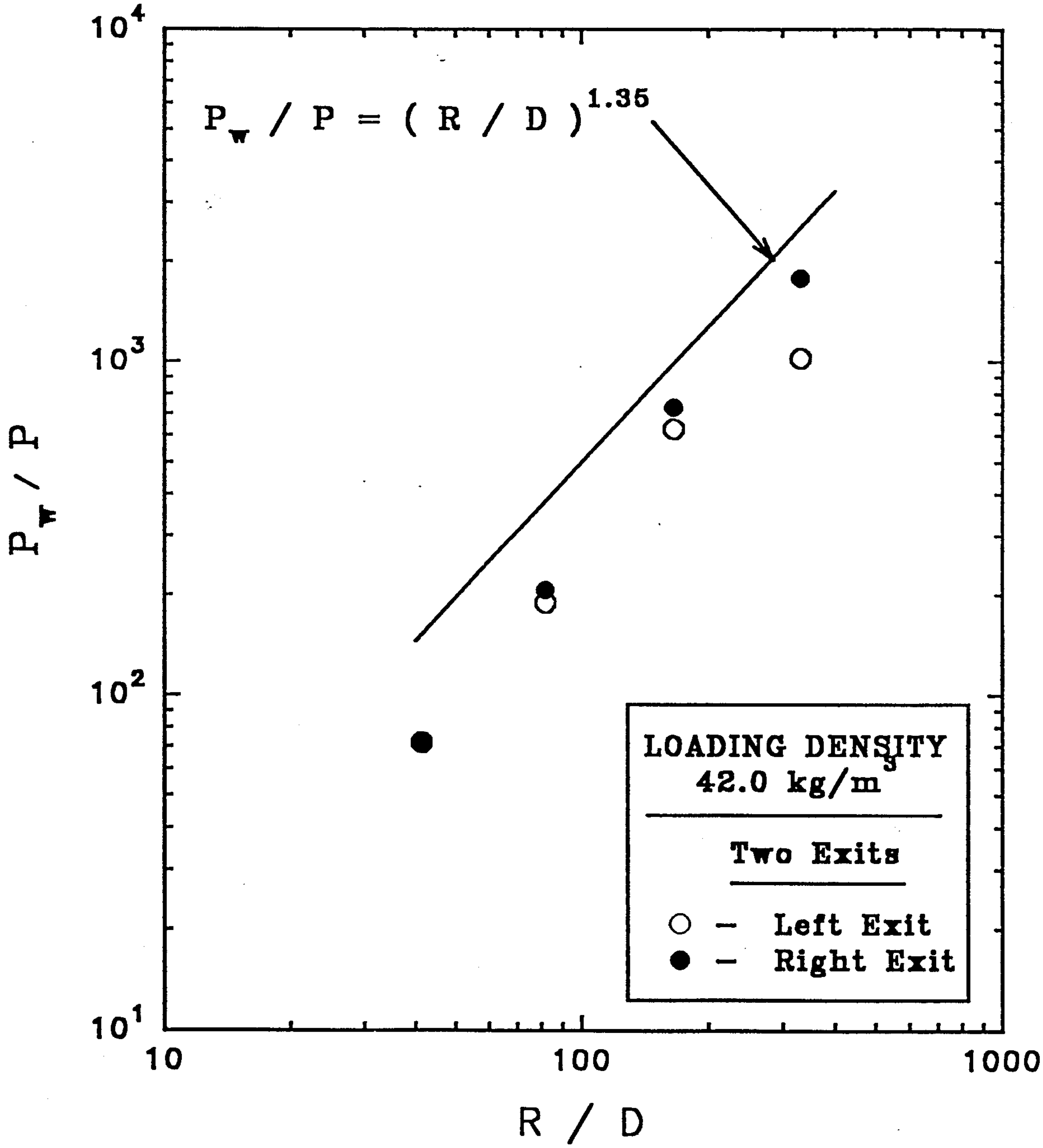


Figure 14. Comparison of normalized free-field overpressures from detonations in chambers with two exits, left side (open circles) versus right side (solid circles) for an explosive loading density of 42.0 kg/m^3.

Figure 15. Comparison of free-field side-on impulse from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

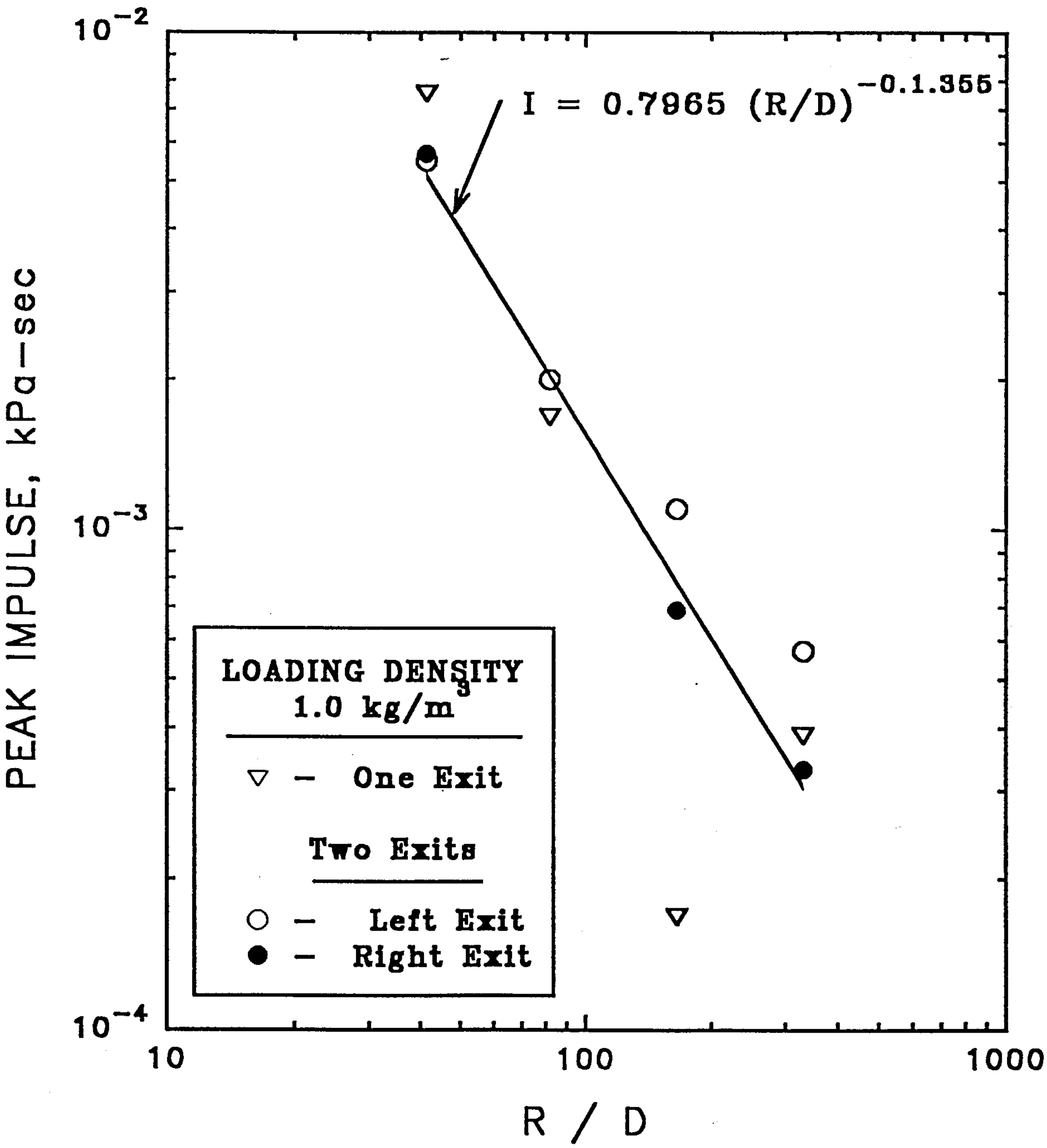
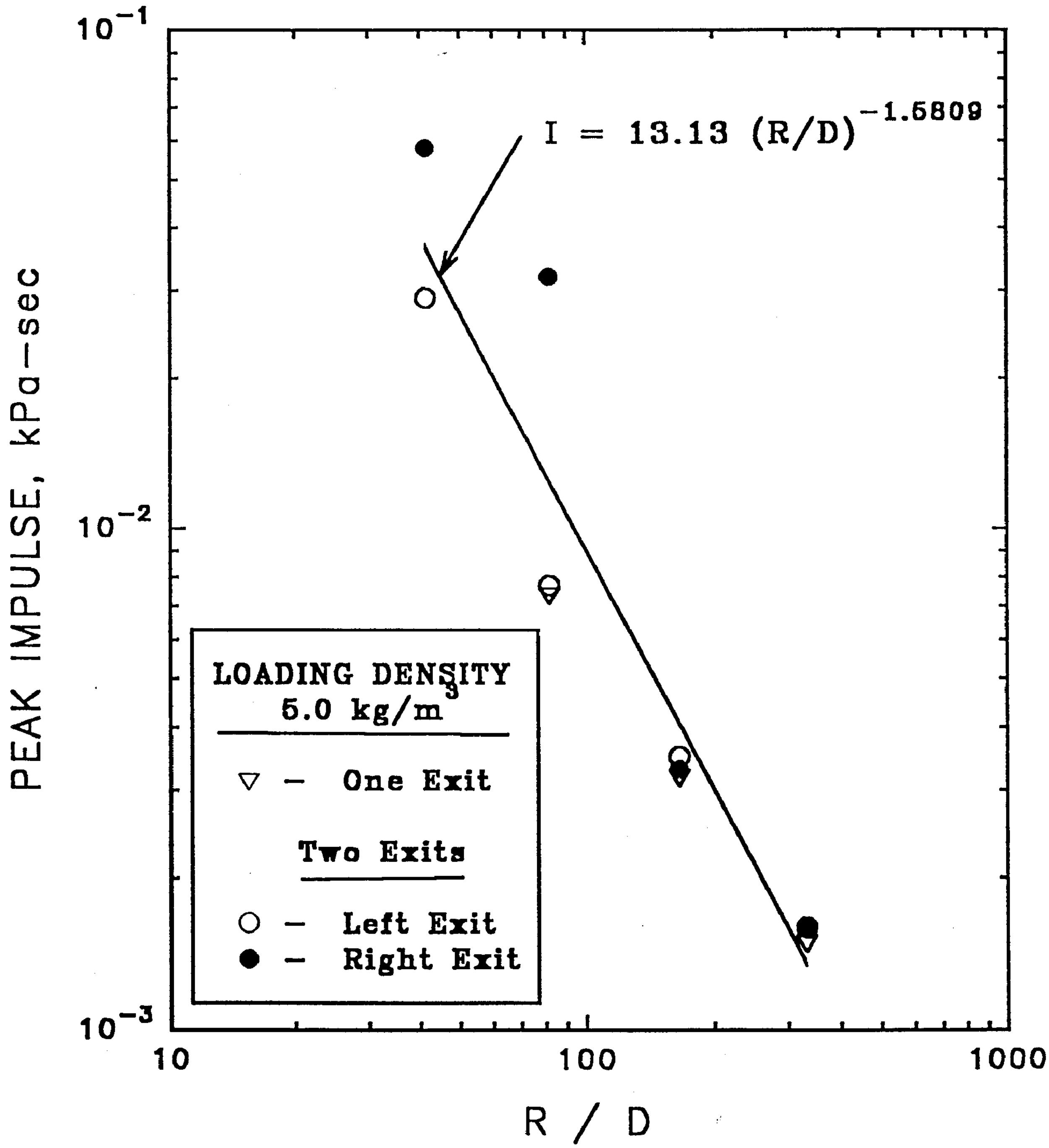


Figure 15. Comparison of free-field side-on impulse from detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 1.0 kg/m³.

Figure 16. Comparison of free-field side-on impulse from detonations In chamberswith two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 5.0 kg/m³.



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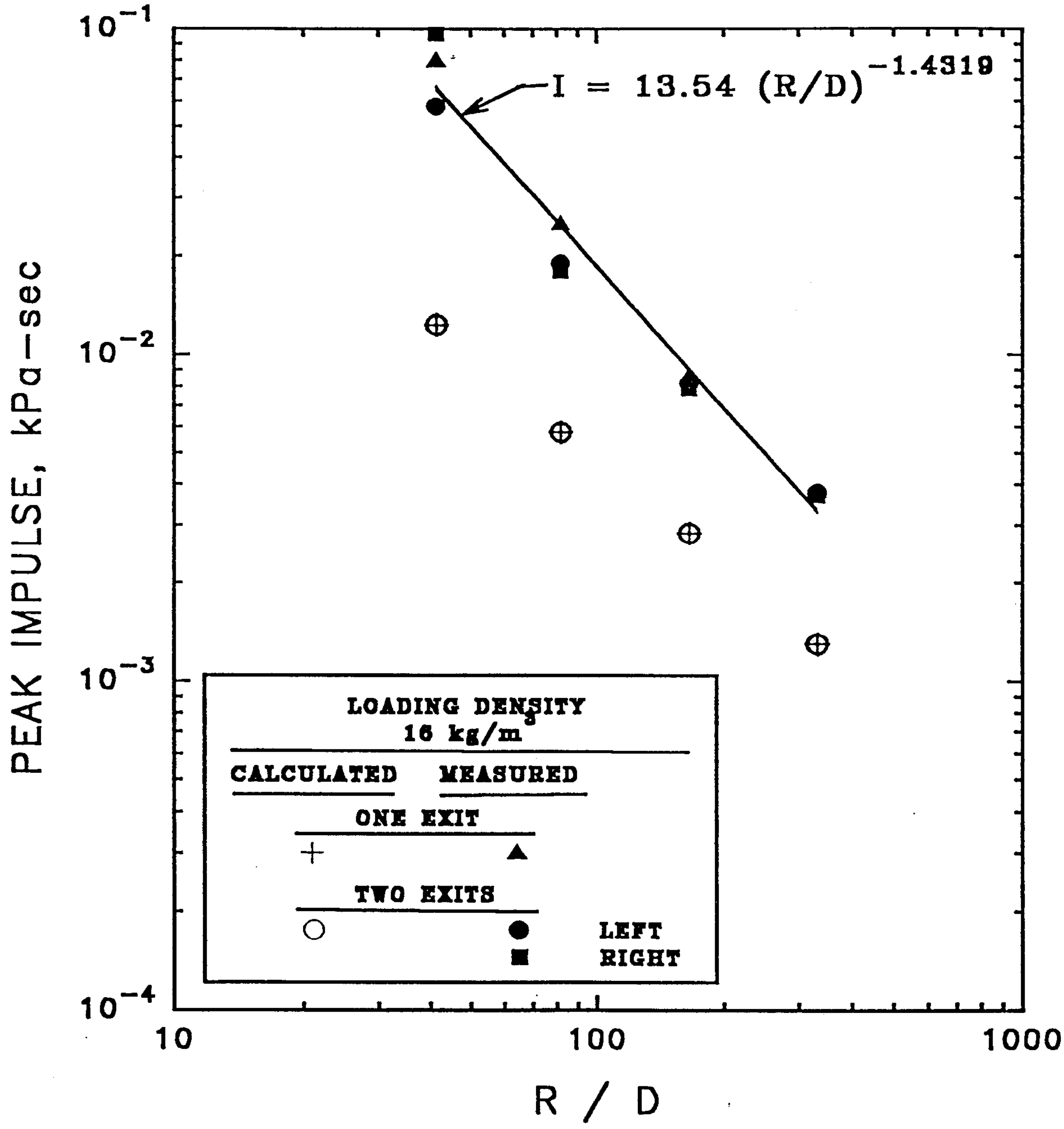
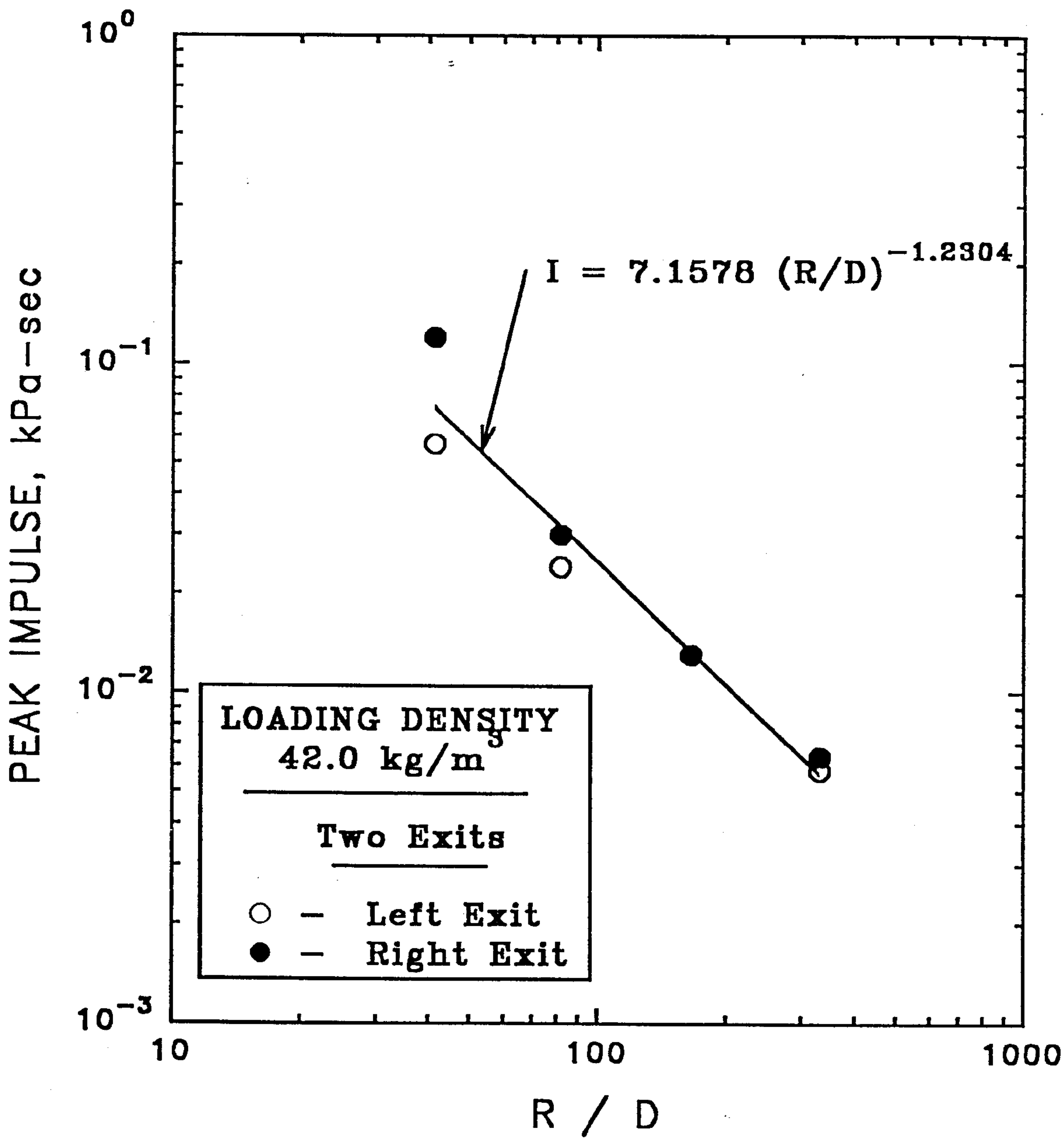


Figure 17. Comparison of free-field side-on impulse from experimental and computational (BLASTX3) models of detonations in chambers with two exits (circles) versus chambers with one exit (triangles), for an explosive loading density of 15.0 kg/m^3.

Figure 18. Comparison of free-field side-on impulse from detonations in chambers with two exits, left side (open circles) versus right side (solid circles) for an explosive loading density of 42.0 kg/m^3.



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